(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 0 503 881 B1

(12) EUROPEAN PATENT SPECIFICATION

(45) Date of publication and mention of the grant of the patent:
29.01.1997 Bulletin 1997/05

(51) Int Cl.^{6}: G01R 33/38, G01R 33/3875

(21) Application number: 92302006.9

(22) Date of filing: 10.03.1992

(54) Magnetic field generating apparatus

Apparat zur Erzeugung eines Magnetfeldes

Appareil pour la génération d'un champ magnétique

(84) Designated Contracting States:
DE FR GB NL

(30) Priority: 13.03.1991 GB 9105286

(43) Date of publication of application:
16.09.1992 Bulletin 1992/38

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- JOURNAL OF PHYSICS E. SCIENTIFIC INSTRUMENTS vol. 22, no. 8, 1 August 1989, BRISTOL GB pages 565 - 573 B.H. SUITS ET AL. 'IMPROVING MAGNETIC FIELD GRADIENT COILS FOR NMR IMAGING'

EP 0 503 881 B1

Printed by Jouve, 75001 PARIS (FR)

Description

The invention relates to magnetic field generating apparatus particularly for use in performing a nuclear magnetic resonance (NMR) experiment.

NMR experiments rely on placing a sample to be examined in a controlled magnetic field, generally having a high homogeneity. MRI magnets have been designed to produce spherical zones of homogeneity by cancelling between axial coil arrays low error order terms, say Z2 and Z4, and as many higher order terms as permited by cost constraints. It is well known that an array of n axial coils will correct up to 2n axial even orders - ie. a four coil magnet corrects Z_2, Z_4, Z_6 (there are always considered an even number of coils symmetrically placed about the midplane of the magnet). The diameter of the homogeneous zone increases as higher orders are cancelled, but it becomes more costly to do this as more coils are needed. Now it happens, that the higher order terms contribute to the net field at a radial point more strongly as the radius of the homogeneous zone increases. Another way of looking at this is to say that as the considered field point is moved out in radius, closer to the inner radius of the coils, the local field contribution of the nearest coil dominates the situation, increasing the rate of field charge with radius. Therefore, it is usual to accept that MRI magnets, comprised of a few discrete coils are designed to produce useable homogeneity over, perhaps half of their bore diameter. It is too costly to correct a large number of high orders by discrete arrays. As the maximum diameter of the object subjected to NMR is increased, the magnet bore size has to be increased therefore in the ratio of, magnet bore diameter is twice maximum subject diameter.

Increasing the diameter of the coil set is costly in superconductor. The following simple analysis shows that for fixed field and conductor hoop stress, cost rises in proportion to the radius cubed.

$V = 2\pi a\ A\ n$, a = coil radius, A = coil cross-section, n = nos turns

Stress in a turn $\sigma \simeq I*Bz*a/A$. I = current, Bz is local axial field $\sigma*I \simeq a*Bo/A, Bo \simeq Bz$ where Bo is the bore field

$$Bo = \mu o * n * I/a,$$

for a simple coil

Substituting for I

$$\text{Cost} = (2\pi/\mu) * a^3 * Bo^2/\sigma$$

Conventional MRI magnets are not satisfactory, therefore, for examining relatively large objects where the areas of interest extend beyond the region which can be placed within the spherical homogeneous region even though the object can be placed within the coils.

EP-A-0187691 discloses a magnetic assembly for use in magnetic resonance imaging apparatus, an examination assembly comprising six electrical coils arranged asymmetrically about an axis. The coils are arranged to generate a substantially uniform magnetic field at a point offset from the geometric centre of the assembly.

EP-A-0404461 discloses a magnetic field assembly for generating magnetic field gradients across the region. The assembly comprises a Y gradient coil assembly, which applies gradients along a Y axis, and a X gradient coil assembly, which selectively applies gradients in the X direction. The gradient coil assemblies include two coils mounted on opposite sides of the examination region, with these coils being arranged symmetrically relative to the axis of the apparatus (conventionally designated the Z axis). In addition to these gradient assemblies, there is also provided a Z gradient coil assembly which includes a pair of annular or other conventional coils for creating gradients on the Z axis.

EP-A-0134701 discloses applying a bias field to the gradient field of an NMR imaging system to offset the nil point in the gradient field from its nominal position. The bias field is induced by a separate bias coil which may take any shape, so long as the fields produce results in an essentially uniform offset in the main field. In the preferred embodiment the bias coil arrangement comprises a pair of current loops forming a Helmholz coil configuration.

In accordance with the present invention, we provide magnetic field generating apparatus comprising a plurality of coaxial coils spaced apart and along an axis characterised in that the apparatus further comprises a solenoid having a plurality of turns about said axis, wherein said coils are positioned relative to each other and to said solenoid such that when working currents flow through said coils and said solenoid a magnetic field is generated within said solenoid, said magnetic field having a zero order component and a first order gradient with high order gradients being substantially balanced, wherein said magnetic field has contours of constant value extending with a radially outward component from said axis of said solenoid, and wherein regions of substantially homogeneous magnetic field for performing an NMR experiment are formed about said contours, said regions extending along said contours and having a substantially constant thickness on either side of said contours.

We have realised that if an odd order gradient is applied to a solenoid, the spherical central region which is normally

present at the centre of a solenoid suitable for NMR is largely removed and a set of saucer shaped high homogeneity planes are generated, there being a gradient between the planes, that extends to the diameter of the solenoid. We are then able to illuminate a subject of given diameter with a coil set of approximately the same diameter, and benefit from the r^3 cost savings. In Table 1 below conductor quantity for 2.OT, 70 MPa MRI magnets, spherical homogeneity is compared with a solenoid of similar length, planar homogeneity, where both are able to illuminate a subject 0.8 m diameter.

TABLE 1

Comparison of a solenoid for planar homogeneous zones and a "standard" MRI magnet	
Comparison at 2.0T 70MPa hoop stress:	
- "MRI array 6 coil"	
Mean coil radius 80cm	
Mean overall length 246cm	
Homogeneous sphere ± 100ppm	80cm
Conductor at 100T cm^{-2}	515554m
- Gradient Solenoid	
Mean coil radius 40cm	
Mean overall length 400cm	
Homogeneous sphere ± 100ppm	80cm
Conductor at 100T cm^{-2}	122447m

A further significant advantage of this apparatus is that the working regions will extend substantially fully across the diameter of the solenoid. Consequently, much larger areas of the sample can be investigated than has previously been possible. For example, inanimate objects such as polymer composites and the like can be investigated.

The gradient field also breaks the symmetry which would otherwise exist on either side of the mid-plane of the solenoid so as to remove further spatial ambiguity.

In contrast to conventional magnets used in NMR in which the low order field terms are balanced, in the present invention a solenoid with a relatively large aspect ratio can be used which will enable higher order error terms to be balanced with the low order error terms remaining to define the axial gradient.

The invention thus envisages the use of low order axial gradients (particularly first order) which are normally eliminated in NMR magnets. It should also be noted that solenoids of practical dimensions, which will possess a positive second order axial gradient can be used. This second order governs the shape of the homogeneous regions but in "pure form" simply dishes the homogeneous regions, while a first order gradient controls the thickness of the homogeneous regions. Preferably, therefore the first order gradient is greater than or equal to the second order gradient.

The invention provides an additional advantage, when considering solid state NMR, which is that the gradient between planar homogeneous zones ensures that it is easier to provide an appropriate RF field. That is an RF field that is orthogonal to the field of the magnet everywhere in the homogeneous zone and follows the same value everywhere in space as a function of time for any pulse sequence.

An example of magnetic field generating apparatus according to the present invention will now be described according to the accompanying drawings, in which:-

Figure 1 illustrates the field profile within a conventional solenoid;
Figure 2 illustrates the field profile within the same solenoid but modified by the addition of a gradient magnetic field generator in accordance with the invention;
Figures 3A-3J illustrate the effect of different Z_1 and Z_2 gradients on the homogeneous regions;
Figure 4 illustrates the coil dimensions referred to in Table 4; and,
Figure 5 shows a cross section through the conductor of the coil of Figure 4.

Figure 1 illustrates contours of constant field which exist in a simple solenoid. The plot is of radius R in cm against axial length Z in cm from mid plane or origin of magnet. The dimensions of the solenoid whose field is illustrated are inner radius = 30cm, outer radius = 31.72cm, length to the mid plane = 75cm and current density = 10,050 A/cm^2. In this Figure, the contours are shown at three different field values separated by 100 gauss (2000, 19900 and 19800

Gauss 1,2,3). The thicknesses of regions of homogeneity centred at ±10 gauss from the nominal value are shown. These regions are generally deeply dished and because of the symmetry about the mid-plane, together with the central spherical region of field homogeneity, the central sections of the regions are thickened and merge with their partners in symmetry. This is unsatisfactory if attempts are made to use the dish shaped regions by reason of ambiguity due to the symmetry, the extreme curvature of the working regions, and also their varying thicknesses.

Figure 2 illustrates the effect of modifying the solenoid so that at least the first order terms are not balanced and a steady linear, axial field gradient is generated. Firstly, the symmetry between the regions on either side of the mid-plane is removed. Secondly, the thickness of the working regions becomes determined more by the gradient and less by the properties of the solenoid. This is shown in Figure 2 in the case of applying a gradient of 10 gauss/cm for 19800, 19900, 20000 Gauss 4,9;5;8;6,7. It can be seen also that the gradient has a beneficial effect on the flatness of the working regions which have substantially constant thicknesses and extend close to the inner circumference of the solenoid. Lines 10,11,12 illustrate the results for application of a gradient of 60 Gauss cm for 19800, 19900 and 20000 Gauss.

A gradient will exist in the axial direction so that when an NMR experiment is performed, it is necessary dynamically to cancel that gradient but this can be done using conventional NMR technniques.

Tables 2 and 3 below set out the coil configurations used to achieve the field profiles shown in Figures 1 and 2 respectively. In these Tables, a1 and a2 are the internal and external radii of the solenoid, while b1 and b2 are the positions of the ends of the solenoid relative to the mid-plane.

TABLE 2

Simple solenoid - contours

Coil # or 0	1.000E+000
J (A/cm2)	1.001E+004
a1 (cm)	3.000E+001
a2	3.172E+001
b1	-7.500E+001
b2	7.500E+001
precision	5.000E+001

Z 0.000E+000

R	Z	dB/dZ	error
4.700E+000	0.000E+000	0.000E+000	2.001E+004
7.200E+000	3.892E+000	-4.994E+000	5.858E-007
9.700E+000	6.096E+000	-7.705E+000	2.929E-007
1.220E+001	8.167E+000	-1.010E+001	6.834E-007
1.470E+001	1.023E+001	-1.230E+001	6.834E-007
1.720E+001	1.233E+001	-1.434E+001	7.810E-007
1.970E+001	1.451E+001	-1.620E+001	6.834E-007
2.220E+001	1.680E+001	-1.789E+001	5.858E-007
2.470E+001	1.923E+001	-1.936E+001	2.929E-007
2.720E+001	2.185E+001	-2.059E+001	1.953E-007
2.970E+001	2.470E+001	-2.150E+001	9.763E-007

Z 2.200E+000

R	Z	dB/dZ	error
0.000E+000	2.200E+000	-2.918E+000	1.999E+004
2.500E+000	2.823E+000	-3.731E+000	3.907E-007
5.000E+000	4.180E+000	-5.477E+000	5.861E-007
7.500E+000	5.797E+000	-7.495E+000	6.838E-007
1.000E+001	7.536E+000	-9.573E+000	7.815E-007
1.250E+001	9.364E+000	-1.162E+001	1.172E-006
1.500E+001	1.128E+001	-1.360E+001	1.270E-006
1.750E+001	1.328E+001	-1.547E+001	1.074E-006
2.000E+001	1.540E+001	-1.721E+001	8.791E-007
2.250E+001	1.765E+001	-1.879E+001	6.838E-007
2.500E+001	2.006E+001	-2.016E+001	0.000E+000
2.750E+001	2.267E+001	-2.129E+001	4.884E-007
3.000E+001	0.000E+000	0.000E+000	0.000E+000

Z 1.170E+001

R	Z	dB/dZ	error
0.000E+000	1.170E+001	-1.631E+001	1.991E+004
2.500E+000	1.185E+001	-1.647E+001	0.000E+000
5.000E+000	1.228E+001	-1.695E+001	6.668E-007
7.500E+000	1.299E+001	-1.769E+001	1.177E-006
1.000E+001	1.394E+001	-1.864E+001	1.668E-006
1.250E+001	1.511E+001	-1.974E+001	2.257E-006
1.500E+001	1.649E+001	-2.092E+001	2.159E-006
1.750E+001	1.806E+001	-2.212E+001	2.159E-006
2.000E+001	1.983E+001	-2.329E+001	1.864E-006
2.250E+001	2.180E+001	-2.435E+001	1.472E-006
2.500E+001	2.400E+001	-2.527E+001	1.079E-006
2.750E+001	2.646E+001	-2.595E+001	1.962E-007
3.000E+001	0.000E+000	0.000E+000	0.000E+000

Z 1.240E+001

R	Z	dB/dZ	error
0.000E+000	1.240E+001	-1.740E+001	1.989E+004
2.500E+000	1.254E+001	-1.755E+001	2.945E-007
5.000E+000	1.296E+001	-1.799E+001	8.836E-007
7.500E+000	1.363E+001	-1.869E+001	1.375E-006
1.000E+001	1.455E+001	-1.959E+001	1.571E-006
1.250E+001	1.569E+001	-2.064E+001	2.258E-006
1.500E+001	1.704E+001	-2.176E+001	2.258E-006
1.750E+001	1.858E+001	-2.291E+001	2.258E-006
2.000E+001	2.033E+001	-2.402E+001	2.258E-006
2.250E+001	2.228E+001	-2.504E+001	1.669E-006
2.500E+001	2.446E+001	-2.590E+001	9.818E-007
2.750E+001	2.691E+001	-2.653E+001	2.945E-007
3.000E+001	0.000E+000	0.000E+000	0.000E+000

Z 1.660E+001

R	Z	dB/dZ	error
0.000E+000	1.660E+001	-2.439E+001	1.981E+004
2.500E+000	1.671E+001	-2.449E+001	4.931E-007
5.000E+000	1.706E+001	-2.460E+001	1.183E-006
7.500E+000	1.762E+001	-2.530E+001	1.381E-006
1.000E+001	1.840E+001	-2.594E+001	2.268E-006
1.250E+001	1.939E+001	-2.670E+001	2.663E-006
1.500E+001	2.059E+001	-2.753E+001	2.958E-006
1.750E+001	2.199E+001	-2.838E+001	2.958E-006
2.000E+001	2.361E+001	-2.919E+001	2.860E-006
2.250E+001	2.546E+001	-2.990E+001	2.465E-006
2.500E+001	2.755E+001	-3.045E+001	1.479E-006
2.750E+001	2.995E+001	-3.073E+001	5.917E-007
3.000E+001	0.000E+000	0.000E+000	0.000E+000

Z 1.710E+001

R	Z	dB/dZ	error
0.000E+000	1.710E+001	-2.528E+001	1.979E+004
2.500E+000	1.721E+001	-2.538E+001	4.934E-007
5.000E+000	1.755E+001	-2.568E+001	1.184E-006
7.500E+000	1.810E+001	-2.616E+001	1.677E-006
1.000E+001	1.887E+001	-2.678E+001	2.368E-006
1.250E+001	1.985E+001	-2.751E+001	2.566E-006
1.500E+001	2.103E+001	-2.831E+001	2.862E-006
1.750E+001	2.242E+001	-2.912E+001	2.960E-006
2.000E+001	2.403E+001	-2.989E+001	2.862E-006
2.250E+001	2.586E+001	-3.057E+001	2.269E-006
2.500E+001	2.796E+001	-3.107E+001	1.776E-006
2.750E+001	3.035E+001	-3.131E+001	5.920E-007
3.000E+001	0.000E+000	0.000E+000	0.000E+000

TABLE 3

Solenoid with 10gauss/cm gradient - contours

Coil # or 0	1.000E+000
J (A/cm2)	1.001E+004
a1 (cm)	3.000E+001
a2	3.172E+001
b1	-7.500E+001
b2	7.500E+001
precision	5.000E+001
Coil # or 0	2.000E+000
J (A/cm2)	1.000E+003
a1 (cm)	3.300E+001
a2	3.700E+001
b1	-3.200E+001
b2	-2.800E+001
precision	5.000E+001
Coil # or 0	3.000E+000
J (A/cm2)	-1.000E+003
a1 (cm)	3.300E+001
a2	3.700E+001
b1	2.800E+001
b2	3.200E+001
precision	5.000E+001

Z -2.430E+001

R	Z	dB/dZ	error
0.000E+000	-2.430E+001	3.469E+001	1.979E+004
2.500E+000	-2.444E+001	3.489E+001	8.882E-007
5.000E+000	-2.485E+001	3.546E+001	3.059E-006
7.500E+000	-2.555E+001	3.645E+001	5.033E-006
1.000E+001	-2.652E+001	3.792E+001	6.908E-006
1.250E+001	-2.779E+001	4.003E+001	8.487E-006
1.500E+001	-2.933E+001	4.314E+001	8.290E-006
1.750E+001	-3.114E+001	4.793E+001	5.329E-006
2.000E+001	-3.312E+001	5.535E+001	3.651E-006
2.250E+001	-3.513E+001	6.538E+001	2.359E-005
2.500E+001	-3.698E+001	7.436E+001	5.053E-005
2.750E+001	-3.856E+001	7.613E+001	1.303E-005

Z -2.390E+001

R	Z	dB/dZ	error
0.000E+000	-2.390E+001	3.349E+001	1.981E+004
2.500E+000	-2.404E+001	3.369E+001	1.085E-006
5.000E+000	-2.446E+001	3.426E+001	3.057E-006
7.500E+000	-2.517E+001	3.525E+001	4.931E-006
1.000E+001	-2.616E+001	3.671E+001	6.903E-006
1.250E+001	-2.744E+001	3.880E+001	8.481E-006
1.500E+001	-2.901E+001	4.187E+001	8.974E-006
1.750E+001	-3.085E+001	4.664E+001	6.213E-006
2.000E+001	-3.287E+001	5.415E+001	2.465E-006
2.250E+001	-3.492E+001	6.454E+001	2.199E-005
2.500E+001	-3.679E+001	7.417E+001	5.237E-005
2.750E+001	-3.838E+001	7.653E+001	1.874E-005

Z -2.080E+001

R	Z	dB/dZ	error
0.000E+000	-2.080E+001	2.490E+001	1.989E+004
2.500E+000	-2.096E+001	2.511E+001	1.080E-006
5.000E+000	-2.145E+001	2.572E+001	3.436E-006
7.500E+000	-2.225E+001	2.674E+001	5.596E-006
1.000E+001	-2.338E+001	2.817E+001	7.657E-006
1.250E+001	-2.483E+001	3.012E+001	9.523E-006
1.500E+001	-2.661E+001	3.289E+001	1.021E-005
1.750E+001	-2.872E+001	3.725E+001	8.246E-006
2.000E+001	-3.106E+001	4.488E+001	2.552E-006
2.250E+001	-3.343E+001	5.757E+001	4.614E-006
2.500E+001	-3.555E+001	7.239E+001	4.850E-005
2.750E+001	-3.723E+001	7.952E+001	6.803E-005

Z -2.030E+001

R	Z	dB/dZ	error
0.000E+000	-2.030E+001	2.363E+001	1.991E+004
2.500E+000	-2.047E+001	2.385E+001	1.177E-006
5.000E+000	-2.096E+001	2.447E+001	3.238E-006
7.500E+000	-2.179E+001	2.550E+001	5.396E-006
1.000E+001	-2.294E+001	2.694E+001	7.457E-006
1.250E+001	-2.442E+001	2.887E+001	9.615E-006
1.500E+001	-2.624E+001	3.159E+001	1.001E-005
1.750E+001	-2.839E+001	3.587E+001	7.751E-006
2.000E+001	-3.079E+001	4.344E+001	2.158E-006
2.250E+001	-3.321E+001	5.638E+001	2.649E-006
2.500E+001	-3.537E+001	7.204E+001	4.513E-005
2.750E+001	-3.708E+001	7.997E+001	7.574E-005

Z -1.540E+001

R	Z	dB/dZ	error
0.000E+000	-1.540E+001	1.276E+001	1.999E+004
2.500E+000	-1.564E+001	1.308E+001	9.768E-007
5.000E+000	-1.633E+001	1.396E+001	3.224E-006
7.500E+000	-1.744E+001	1.532E+001	4.982E-006
1.000E+001	-1.892E+001	1.704E+001	6.154E-006
1.250E+001	-2.074E+001	1.906E+001	6.935E-006
1.500E+001	-2.294E+001	2.149E+001	5.373E-006
1.750E+001	-2.555E+001	2.488E+001	3.517E-006
2.000E+001	-2.852E+001	3.120E+001	2.794E-005
2.250E+001	-3.151E+001	4.504E+001	1.993E-005
2.500E+001	-3.406E+001	6.772E+001	8.010E-006
2.750E+001	-3.600E+001	8.384E+001	1.261E-004

Z -1.450E+001

R	Z	dB/dZ	error
0.000E+000	-1.450E+001	1.104E+001	2.001E+004
2.500E+000	-1.476E+001	1.139E+001	1.269E-006
5.000E+000	-1.552E+001	1.237E+001	3.319E-006
7.500E+000	-1.671E+001	1.384E+001	4.784E-006
1.000E+001	-1.827E+001	1.565E+001	5.858E-006
1.250E+001	-2.017E+001	1.774E+001	6.053E-006
1.500E+001	-2.244E+001	2.017E+001	4.296E-006
1.750E+001	-2.513E+001	2.344E+001	6.444E-006
2.000E+001	-2.819E+001	2.950E+001	3.583E-005
2.250E+001	-3.128E+001	4.325E+001	3.183E-005
2.500E+001	-3.390E+001	6.688E+001	1.630E-005
2.750E+001	-3.567E+001	8.439E+001	1.283E-004

Z -7.000E-001

R	Z	dB/dZ	error
0.000E+000	-7.000E-001	-9.716E+000	2.001E+004
2.500E+000	-4.906E-001	-9.996E+000	9.763E-006
5.000E+000	1.042E-001	-1.078E+001	9.763E-008
7.500E+000	1.005E+000	-1.192E+001	3.905E-007
1.000E+001	2.137E+000	-1.328E+001	5.856E-007
1.250E+001	3.447E+000	-1.475E+001	1.074E-006
1.500E+001	4.905E+000	-1.630E+001	1.464E-006
1.750E+001	6.499E+000	-1.792E+001	2.246E-006
2.000E+001	8.230E+000	-1.964E+001	2.538E-006
2.250E+001	1.011E+001	-2.152E+001	3.222E-006
2.500E+001	1.216E+001	-2.367E+001	4.101E-006
2.750E+001	1.442E+001	-2.621E+001	4.101E-006

Z 3.000E-001

R	Z	dB/dZ	error
0.000E+000	3.000E-001	-1.104E+001	1.999E+004
2.500E+000	4.848E-001	-1.128E+001	1.954E-007
5.000E+000	1.017E+000	-1.197E+001	1.954E-007
7.500E+000	1.839E+000	-1.299E+001	3.907E-007
1.000E+001	2.892E+000	-1.424E+001	7.815E-007
1.250E+001	4.131E+000	-1.563E+001	1.075E-006
1.500E+001	5.526E+000	-1.711E+001	1.465E-006
1.750E+001	7.066E+000	-1.869E+001	2.149E-006
2.000E+001	8.748E+000	-2.040E+001	2.637E-006
2.250E+001	1.058E+001	-2.229E+001	3.321E-006
2.500E+001	1.258E+001	-2.449E+001	4.669E-006
2.750E+001	1.480E+001	-2.713E+001	5.275E-006

Z 6.200E+000

R	Z	dB/dZ	error
0.000E+000	6.200E+000	-1.892E+001	1.991E+004
2.500E+000	6.312E+000	-1.905E+001	0.000E+000
5.000E+000	6.645E+000	-1.945E+001	2.943E-007
7.500E+000	7.167E+000	-2.009E+001	2.943E-007
1.000E+001	7.923E+000	-2.093E+001	3.925E-007
1.250E+001	8.637E+000	-2.198E+001	9.811E-007
1.500E+001	9.915E+000	-2.321E+001	1.275E-006
1.750E+001	1.115E+001	-2.467E+001	1.864E-006
2.000E+001	1.253E+001	-2.642E+001	2.845E-006
2.250E+001	1.406E+001	-2.859E+001	4.808E-006
2.500E+001	1.574E+001	-3.143E+001	8.144E-006
2.750E+001	1.762E+001	-3.534E+001	1.521E-005

Z 6.800E+000

R	Z	dB/dZ	error
0.000E+000	6.800E+000	-1.973E+001	1.989E+004
2.500E+000	6.906E+000	-1.986E+001	9.617E-008
5.000E+000	7.230E+000	-2.024E+001	9.617E-006
7.500E+000	7.754E+000	-2.066E+001	2.945E-007
1.000E+001	8.467E+000	-2.169E+001	5.890E-007
1.250E+001	9.356E+000	-2.271E+001	6.835E-007
1.500E+001	1.041E+001	-2.393E+001	1.276E-006
1.750E+001	1.161E+001	-2.539E+001	1.963E-006
2.000E+001	1.296E+001	-2.716E+001	2.749E-006
2.250E+001	1.446E+001	-2.935E+001	4.418E-006
2.500E+001	1.611E+001	-3.234E+001	6.541E-006
2.750E+001	1.794E+001	-3.647E+001	1.669E-005

Z 1.080E+001

R	Z	dB/dZ	error
0.000E+000	1.080E+001	-2.526E+001	1.961E+004
2.500E+000	1.089E+001	-2.537E+001	0.000E+000
5.000E+000	1.115E+001	-2.568E+001	2.959E-007
7.500E+000	1.158E+001	-2.619E+001	0.000E+000
1.000E+001	1.217E+001	-2.691E+001	2.959E-007
1.250E+001	1.292E+001	-2.784E+001	3.945E-007
1.500E+001	1.381E+001	-2.902E+001	5.917E-007
1.750E+001	1.483E+001	-3.053E+001	6.903E-007
2.000E+001	1.598E+001	-3.252E+001	1.163E-006
2.250E+001	1.724E+001	-3.526E+001	3.057E-006
2.500E+001	1.862E+001	-3.929E+001	8.382E-006
2.750E+001	2.013E+001	-4.562E+001	2.456E-005

Z 1.120E+001

R	Z	dB/dZ	error
0.000E+000	1.120E+001	-2.583E+001	1.979E+004
2.500E+000	1.129E+001	-2.593E+001	2.960E-007
5.000E+000	1.154E+001	-2.623E+001	0.000E+000
7.500E+000	1.197E+001	-2.674E+001	1.973E-007
1.000E+001	1.255E+001	-2.745E+001	9.867E-008
1.250E+001	1.328E+001	-2.837E+001	9.867E-008
1.500E+001	1.415E+001	-2.955E+001	1.973E-007
1.750E+001	1.516E+001	-3.107E+001	1.973E-007
2.000E+001	1.629E+001	-3.308E+001	9.867E-007
2.250E+001	1.753E+001	-3.589E+001	2.368E-006
2.500E+001	1.888E+001	-4.006E+001	7.992E-006
2.750E+001	2.035E+001	-4.668E+001	2.457E-005

```
Solenoid with 60gauss/cm gradient - contours
Coil # or 0   1.000E+000
J (A/cm2)   1.001E+004
a1 (cm)     3.000E+001
a2          3.172E+001
b1         -7.500E+001
b2          7.500E+001
precision   5.000E+001
Coil # or 0   2.000E+000
J (A/cm2)   6.000E+003
a1 (cm)     3.300E+001
a2          3.700E+001
b1         -3.200E+001
b2         -2.800E+001
precision   5.000E+001
Coil # or 0   3.000E+000
J (A/cm2)  -6.000E+003
a1 (cm)     3.300E+001
a2          3.700E+001
b1          2.800E+001
b2          3.200E+001
precision   5.000E+001
```

Z 0.000E+000

R	Z	dB/dZ	error
0.000E+000	0.000E+000	-6.386E+001	2.000E+004
2.500E+000	3.485E-002	-6.391E+001	0.000E+000
5.000E+000	1.386E-001	-6.404E+001	1.953E-007
7.500E+000	3.105E-001	-6.418E+001	9.767E-008
1.000E+001	5.496E-001	-6.423E+001	6.837E-007
1.250E+001	8.575E-001	-6.405E+001	1.660E-006
1.500E+001	1.240E+000	-6.346E+001	2.037E-006
1.750E+001	1.709E+000	-6.231E+001	4.666E-006
2.000E+001	2.289E+000	-6.043E+001	6.739E-006
2.250E+001	3.022E+000	-5.772E+001	9.962E-006
2.500E+001	3.979E+000	-5.420E+001	1.318E-005
2.750E+001	5.277E+000	-4.995E+001	1.563E-005

Z 1.500E+000

R	Z	dB/dZ	error
0.000E+000	1.500E+000	-6.583E+001	1.990E+004
2.500E+000	1.534E+000	-6.588E+001	1.963E-007
5.000E+000	1.635E+000	-6.600E+001	9.814E-008
7.500E+000	1.804E+000	-6.614E+001	0.000E+000
1.000E+001	2.043E+000	-6.621E+001	5.889E-007
1.250E+001	2.355E+000	-6.608E+001	1.668E-006
1.500E+001	2.751E+000	-6.563E+001	3.141E-006
1.750E+001	3.246E+000	-6.471E+001	4.711E-006
2.000E+001	3.869E+000	-6.319E+001	7.557E-006
2.250E+001	4.668E+000	-6.101E+001	1.138E-005
2.500E+001	5.718E+000	-5.817E+001	1.570E-005
2.750E+001	7.140E+000	-5.473E+001	1.914E-005

Z 3.000E+000

R	Z	dB/dZ	error
0.000E+000	3.000E+000	-6.780E+001	1.960E+004
2.500E+000	3.033E+000	-6.785E+001	9.864E-006
5.000E+000	3.132E+000	-6.798E+001	1.973E-007
7.500E+000	3.298E+000	-6.816E+001	1.973E-007
1.000E+001	3.535E+000	-6.831E+001	5.918E-007
1.250E+001	3.849E+000	-6.833E+001	1.576E-006
1.500E+001	4.253E+000	-6.811E+001	2.861E-006
1.750E+001	4.766E+000	-6.753E+001	4.932E-006
2.000E+001	5.421E+000	-6.651E+001	6.286E-006
2.250E+001	6.266E+000	-6.500E+001	1.282E-005
2.500E+001	7.379E+000	-6.301E+001	1.864E-005
2.750E+001	8.881E+000	-6.056E+001	2.407E-005

The affect of Z1 and Z2 gradients can be seen from Figure 3 which illustrates plots obtained by computer simulation of contours defining a field variation of ±100ppm relative to the centre of the region. Figures 3A-3E relate to a Z1 component with a homogeneity of 500ppm at a 25cm radius with Z2 varying from 100 to 500ppm in steps of 100ppm starting at 100 pp, at 3A. Figures 3F-3J were obtained for a component with a homogeneity Z1 of 1000 ppm and Z2 varying from 200ppm to 1000ppm in 200ppm steps starting at 200ppm for 3F.

The dark plot indicates positive distortion and the light plot negative distortion.

It can be seen that an increase in the Z2 component causes an increased dishing of the homogeneous region while an increase in the Z1 gradient causes the region to narrow.

An example of a coil configuration suitable for this invention is set out in Table 4 below. The dimensions quoted are illustrated in Figure 4. Figure 5 is a cross section through the conductor. The reference numerals in Figures 4 and 5 refer to dimensions shown in the table as follows. B_1; 13; B_2, 14; midplane 15; centre line 16; A_1; 18; A_2; 17; δ_r; 19; δ_z, 20.

$$AA = (A_2 - A_1)/2$$

$$\Delta B = B_2 - B_1$$

$$BA = (B_2 + B_1)/2$$

The system of Table 4 is effectively a combined dipole (coils 1 and 2) and quadrupole (coils 3-5).

The dipole is essentially a solenoid (coil 1) with correcting pair (coil 2). This system produces

Z0 = 48.5 Gauss/Amp ≡ 2 Tesla at 412.33 Amps
Z2 = 41 ppm on 25 cm radius
Z4 = 26 ppm
Z6 = -105 ppm
Z8 = -15 ppm
Z10, Z12 are <l1ppm

The quadrupole is essentially a "z gradient" coil set, outside the dipole. The field harmonics are

Z1 = 0.4144 Gauss/Amp on 25cm radius ≡ ± 100ppm of 2T in 5.6mm δz
Z3 = -1 ppm
Z5 = -5 ppm
Z7 = -10 ppm
Z9 = -1.5 ppm
Z11 = -1.4 ppm

Table 4

Coil No	A1 cm	A2 cm	ΔA cm	AA cm	Sr mm	LAYERS	B1 cm
1	42	43.896	1.896	42.948	1.58	12	-100
2	44.706	45.97	1.264	45.338	1.58	8	62.7457
3	50.5	50.816	0.316	50.658	1.58	2	61.56
4	50.5	50.846	0.346	50.658	1.58	2	40.964
5	50.5	50.846	0.346	50.658	1.58	2	17.556

B2 cm	ΔB cm	BA cm	Sz mm	Turn/ LAYER	TD TURN/cm^2	TURNS	WDG LENGTH m
100	200	0	2.96		21.382	8108	21880
76.5687	13.82	69.6557	2.96		01.382	374 x 2	2128
70.44	8.88	66	2.96		21.382	± 60 x 2	382
43.036	2.072	42	2.96		21.382	± 14 x 2	89
18.444	0.888	18	2.96		21.382	± 6 x 2	38

Claims

1. A magnetic field generating apparatus, comprising:
   a plurality of coaxial coils spaced apart and along an axis characterised in that the apparatus further comprises a solenoid having a plurality of turns about said axis, wherein said coils are positioned relative to each other and to said solenoid such that when working currents flow through said coils and said solenoid a magnetic field is generated within said solenoid, said magnetic field having a zero order component and a first order gradient with high order gradients being substantially balanced, wherein said magnetic field has contours of constant value extending with a radially outward component from said axis of said solenoid, and wherein regions of substantially homogeneous magnetic field for performing an NMR experiment are formed about said contours, said regions extending along said contours and having a substantially constant thickness on either side of said contours.

2. The magnetic field generating apparatus according to claim 1, wherein said magnetic field generated by said solenoid and said coils further includes a second order gradient, said first order being at least equal to said second order gradient.

3. The magnetic field generating apparatus according to any of the preceding claims, wherein said coils are positioned radially outwardly from said solenoid.

Patentansprüche

1. Ein ein magentisches Feld erzeugendes Gerät, das aufweist:
eine Vielzahl koaxialer Spulen, die voneinander und entlang einer Achse beabstandet sind, gekennzeichnet dadurch, daß das Gerät weiterhin einen Solenoid aufweist, der eine Vielzahl von Windungen um die Achse besitzt, wobei die Spulen relativ zueinander und zu dem Solenoid derart positioniert sind, daß dann, wenn Arbeitsströme durch die Spulen und den Solenoid fließen, ein magnetisches Feld innerhalb des Solenoids erzeugt wird, wobei das magnetische Feld eine Komponente nullter Ordnung und einen Gradienten erster Ordnung mit Gradienten hoher Ordnung, die im wesentlichen ausbalanciert sind, besitzt, wobei das magnetische Feld Konturen eines konstanten Werts besitzt, der sich mit einer radial nach außen gerichteten Komponeten von der Achse des Solenoids erstreckt, und wobei Bereiche eines im wesentlichen homogenen magnetischen Felds zum Durchführen eines NMR-Experiments um die Konturen gebildet sind, wobei sich die Bereiche entlang der Konturen erstrecken und eine im wesentlichen konstante Dicke auf jeder der Seite der Konturen besitzen.

2. Ein ein magnetisches Feld erzeugendes Gerät nach Anspruch 1, wobei das magnetische Feld, das durch den Solenoid und durch die Spulen erzeugt ist, weiterhin einen Gradienten zweiter Ordnung umfaßt, wobei derjenige erster Ordnung mindestens gleich zu dem Gradienten zweiter Ordnung ist.

3. Ein ein magnetisches Feld erzeugendes Gerät gemäß einem der vorhergehenden Ansprüche, wobei die Spulen radial nach außen von dem Solenoid positioniert sind.

Revendications

1. Appareil générateur de champ magnétique comprenant :
plusieurs bobines coaxiales espacées et le long d'un axe, caractérisé en ce que l'appareil comprend en outre un solénoïde comportant plusieurs tours autour dudit axe, en ce que lesdites bobines sont positionnées les unes par rapport aux autres et par rapport audit solénoïde de façon telle que lorsque des courants de mise en oeuvre s'écoulent dans lesdites bobines et dans ledit solénoïde il se produit un champ magnétique à l'intérieur dudit solénoïde, ledit champ magnétique ayant une composante d'ordre zéro et un gradient du premier ordre avec des gradients d'ordres élevés qui sont sensiblement équilibrés ; en ce que ledit champ magnétique a des contours d'une valeur constante s'étendant avec une composante radialement vers l'extérieur dudit axe dudit solénoïde ; et en ce que des régions de champ magnétique sensiblement homogène pour effectuer une expérience de NMR (résonance magnétique nucléaire) se forment autour desdits contours, lesdites régions s'étendant le long desdits contours et ayant une épaisseur sensiblement constante de chaque côté desdits contours.

2. Appareil générateur de champ magnétique selon la revendication 1, dans lequel ledit champ magnétique produit par ledit solénoïde et lesdites bobines comprend en outre un gradient du second ordre, ledit premier ordre étant au moins égal audit gradient du second ordre.

3. Appareil générateur de champ magnétique selon l'une quelconque des revendications précédentes, dans lequel lesdites bobines sont positionnées radialement vers l'extérieur dudit solénoïde.

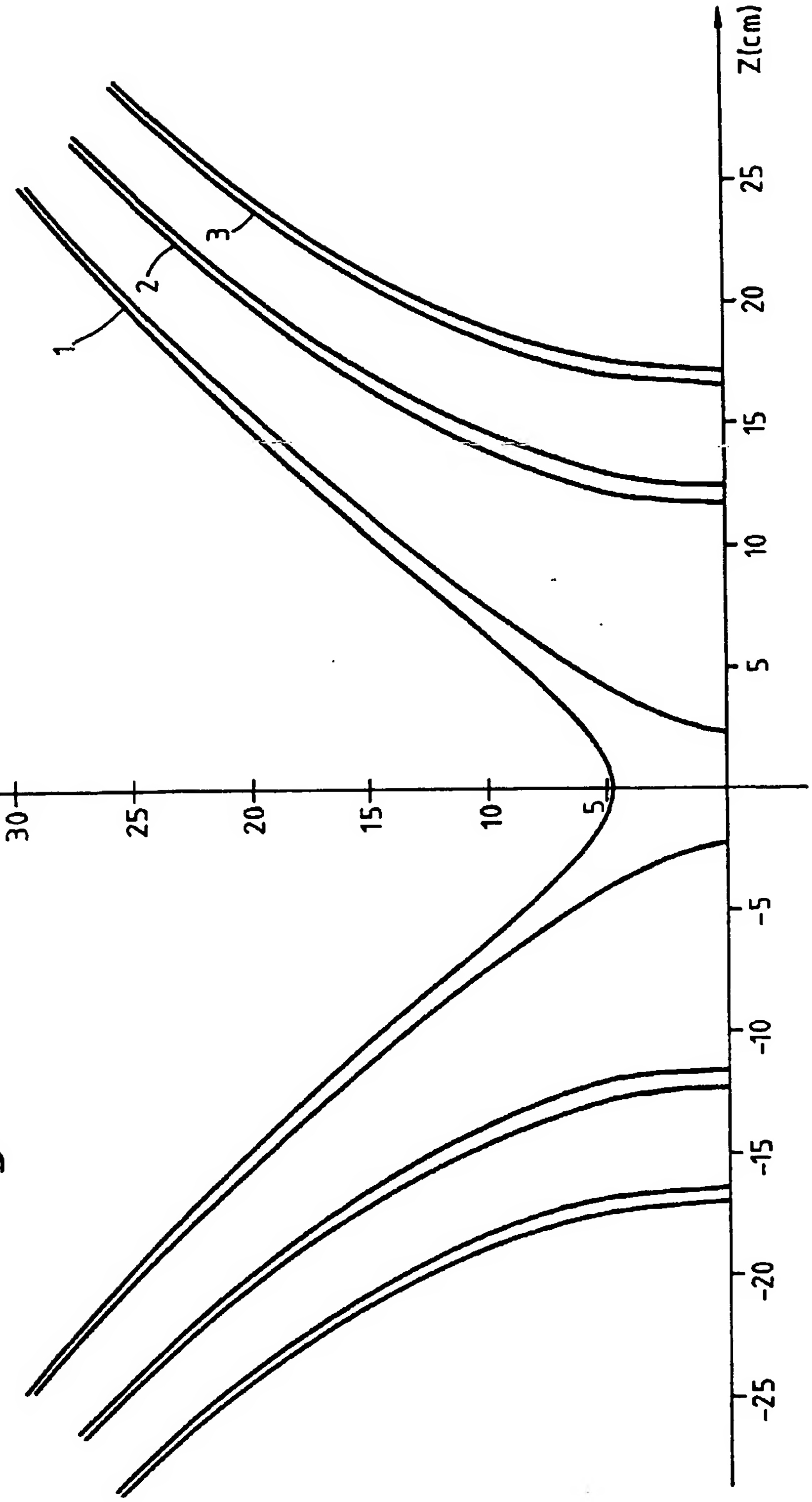

Fig.1.

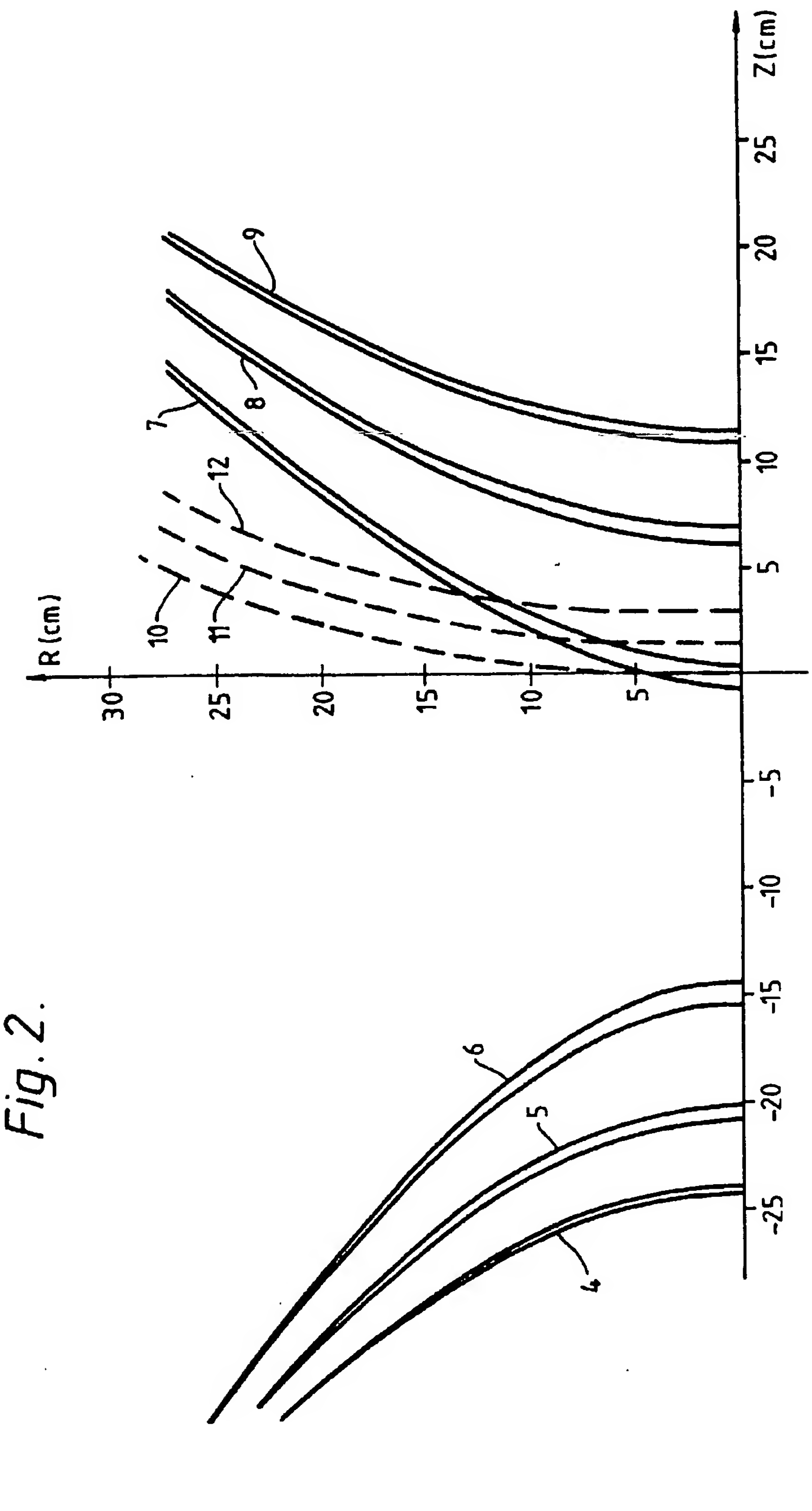

Fig. 2.

Fig. 3A.

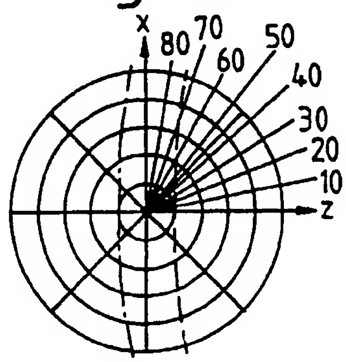

Fig. 3B.

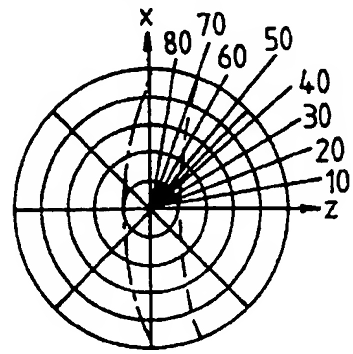

Fig. 3C.

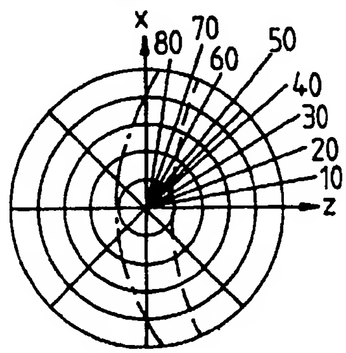

Fig. 3D.

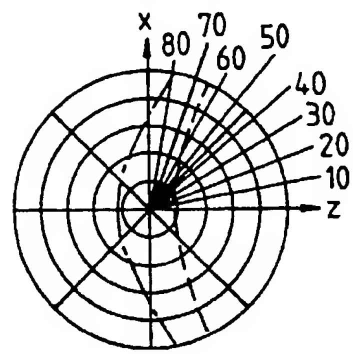

Fig. 3E.

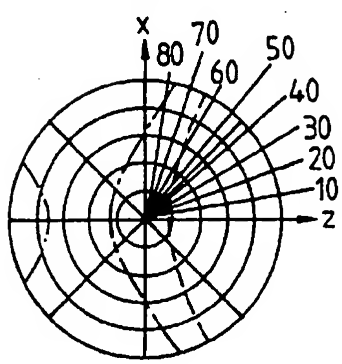

Fig. 3F.

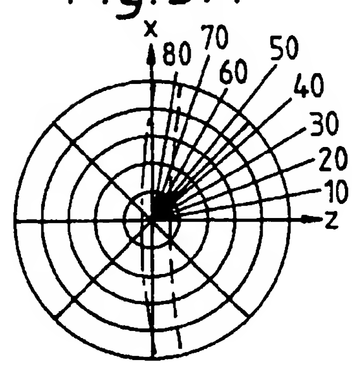

Fig. 3G.

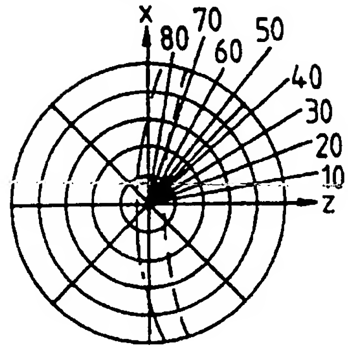

Fig. 3H

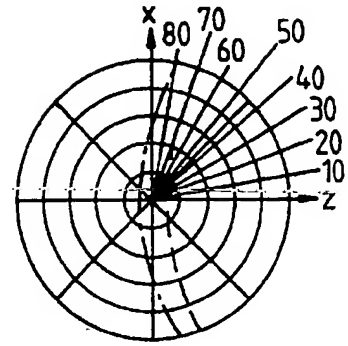

Fig. 3I.

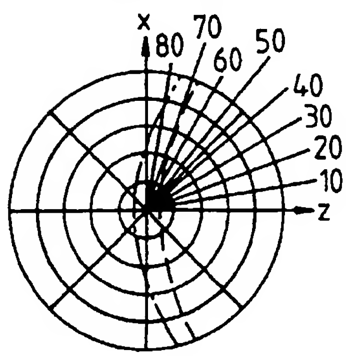

Fig. 3J.

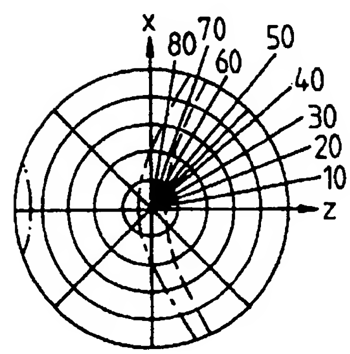

Fig. 4.

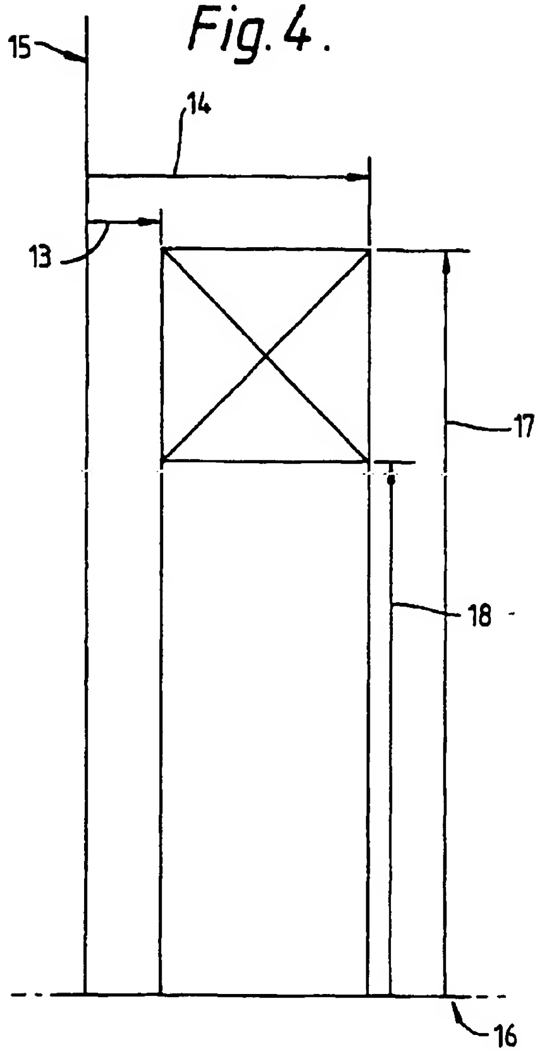

Fig. 5.

$\Delta A = A_2 - A_1$

$AA = (A_2 + A_1)/2$

$\Delta B = B_2 - B_1$

$BA = (B_2 + B_1)/2$